Steering with the head: The visual strategy of a racing driver

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We studied the eye movements of a racing driver during high-speed practice to see whether he took in visual information in a different way from a normal driver on a winding road [1, 2]. We found that, when cornering, he spent most of the time looking close to, but not exactly at, the tangent points on the inside edges of the bends. Each bend was treated slightly differently, and there was a highly repeatable pattern to the way the track edge was viewed throughout each bend. We also found a very close relationship between the driver's head direction and the rate of rotation of the car 1 s later. We interpret these observations as indicating that the driver's gaze is not driven directly by tangent point location, as it is in ordinary driving. Instead, we propose that his head direction is driven by the same information that he uses to control steering and speed, namely his knowledge of the track and his racing line round it. If he directs his head at an angle proportional to his estimate of car rotation speed, this will automatically bring his head roughly into line with the tangent points of the bends. From this standardized position, he can use the expected movements of the tangent points in his field of view to verify, and if necessary modify, his racing line during the following second.

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Results and discussion

The task of a racing driver differs in a number of ways from that of an ordinary driver steering on a winding road. First, he drives 2–3 times faster. Second, he is not obliged to stay in the lane and follow each curve around; instead, he takes a "racing line" around each bend whose curvature profile is not identical with the bend itself. Third, he has to drive as fast as is consistent with maintaining lateral traction, and this imposes a relationship between bend curvature and speed that does not apply in ordinary low-speed driving. Fourth, a racing driver on a familiar track will be driving largely from memory, only using landmarks such as curve apexes as timing cues, rather than having them directly dictate his course. For all of these reasons, we thought that it would be of interest to compare the eye movements of a racing driver with those of ordinary drivers on normal roads [1, 2].

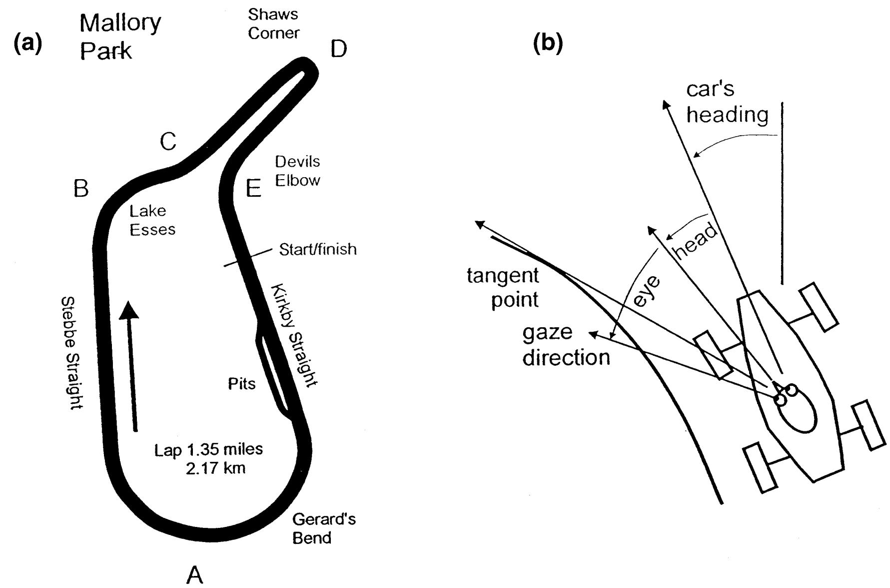
We examined the eye and head movements of Tomas Scheckter, then a Formula 3 racing driver, as he drove practice laps round the Mallory Park circuit in Leicestershire at full speed in rainy conditions (Figures 1a and 2). This unique opportunity was made possible by Uden Associates, who were making a television program on racing drivers for Equinox (U.K. Channel 4) and who invited us to participate. Eye movements were measured using two cameras, one attached to the top of the helmet, facing forward, and a second pointing toward the eye through the visor. The images were combined to give a view in which the upper 2/3 comprised the scene ahead and the lower 1/3 contained the eye. Eye direction was established by manually fitting a computer model of the eye to the eye on the video, frame by frame. This generated eye direction relative to the head, the coordinates of which were used to position a dot on the view of the scene (Figure 2). The vertical movements were not analyzed because there was too much vertical vibration; however, the horizontal movements were adequately stable, and they were measured with an accuracy of 1°–2°. It was also possible to study head movements: a radio aerial located about 1.5 m in front of the driver served as a marker, and its movement in the field of view of the scene camera allowed head rotation to be measured relative to the car's axis (Figure 2). The rate of rotation of the car's heading, relative to the surroundings, was also obtained from the scene camera (see below). These measurements are shown in Figure 1b.

Six laps of the circuit were analyzed, the last three of which involved several overtaking maneuvers that we will consider elsewhere. The circuit has five bends (Figure 1a): a long high-speed bend of roughly constant curvature (A), a pair of bends forming an "S" (B and C), a hairpin (D), and a short bend leading into a fast straight (E). Because of the angular extent of A and D (180°), the driver cannot take a much shallower line round them. In B, C, and E, however, the corners can be cut and a racing line can be adopted.

Does the driver look in similar places on each bend?

Scheckter did indeed look close to the tangent point on all bends (Figure 3). (The tangent point is the nonstationary

Figure 1

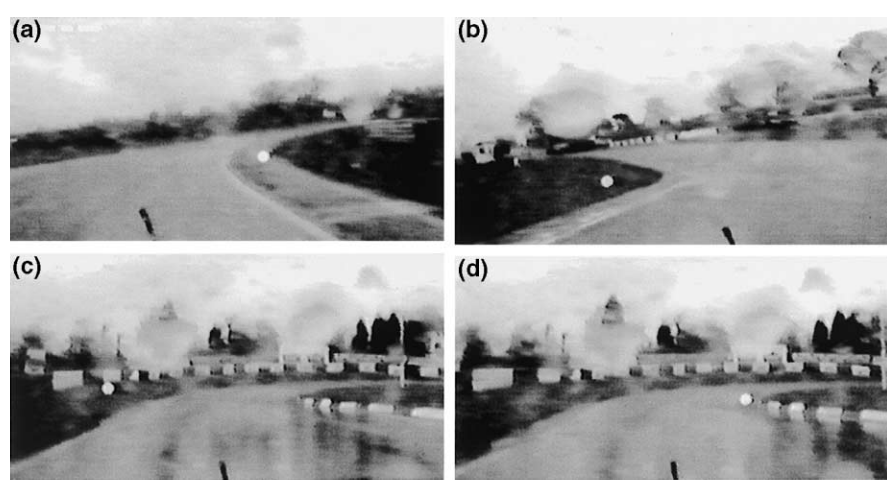


(a) The Mallory Park circuit, with bends described in the text. **(b)** The angles measured in this study. The tangent point is the point at which the driver's line of sight just grazes the edge of the track on the inside of a bend.

point on a bend where the driver's line of sight is tangential to the inner edge of the road, as in Figure 1b. On long bends, the tangent point travels around the curve with the driver: on bend A, it is visible for about 12 s. However, on shallow bends such as B and C, the tangent point becomes a single stationary point, referred to as the apex, which the driver usually aims to "clip". Thus, "tangent point" is the more general term, but "apex" will be used where appropriate). Figure 3 shows that the different bends are not all viewed in quite the same way. On bend A, the gaze was directed accurately at the tangent point throughout the bend (Figure 2a). This was almost true of bend B and the hairpin D, although the spread of gaze was larger. On bend C, the gaze was slightly to the left of the tangent point, i.e., on the bank outside the track (Figure 2b), and it is possible that the driver was looking beyond the corner to the short straight leading to the hairpin. On bend E, the histogram was bimodal. The smaller distribution, nearest the tangent point, was from the first part of the bend, but Scheckter's gaze strayed further to the right as he accelerated into the fast straight. Thus, there were differences, and, in general, it did not seem that the driver's gaze was "locked" to tangent points. Only the large bend A produced visual behavior that looked like that of ordinary drivers (see [1]).

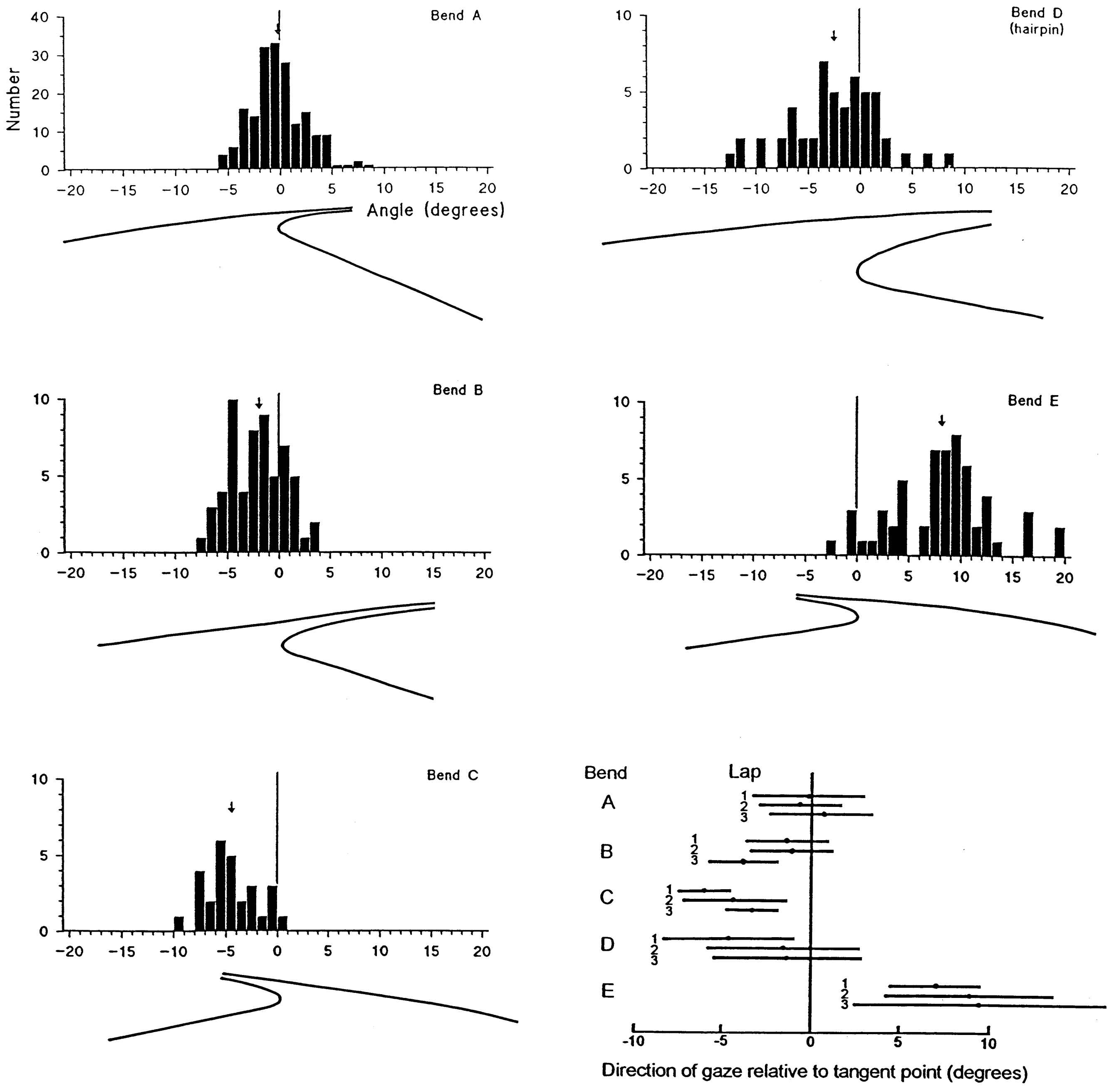
If, as it appears, the driver is not actually tracking tangent points, one might expect to see changes in the position

Figure 2



Four frames from the eye movement record. The white dot shows the direction of the driver's fovea and is approximately 1° wide. The black object at the bottom of each frame is a telemetry aerial in front of the driver, and it indicates the car's approximate heading. The smudges on the upper part of each frame are raindrops on the visor. **(a)** Bend A (Gerard's), showing the gaze directed exactly on the tangent point. **(b)** Bend C, with gaze off the track. The vertical position is uncertain, and Scheckter may be looking beyond the bend. **(c,d)** Approaching the hairpin (D), showing the gaze alternating between the markers to the left of the track and the tangent point to the right .

Figure 3



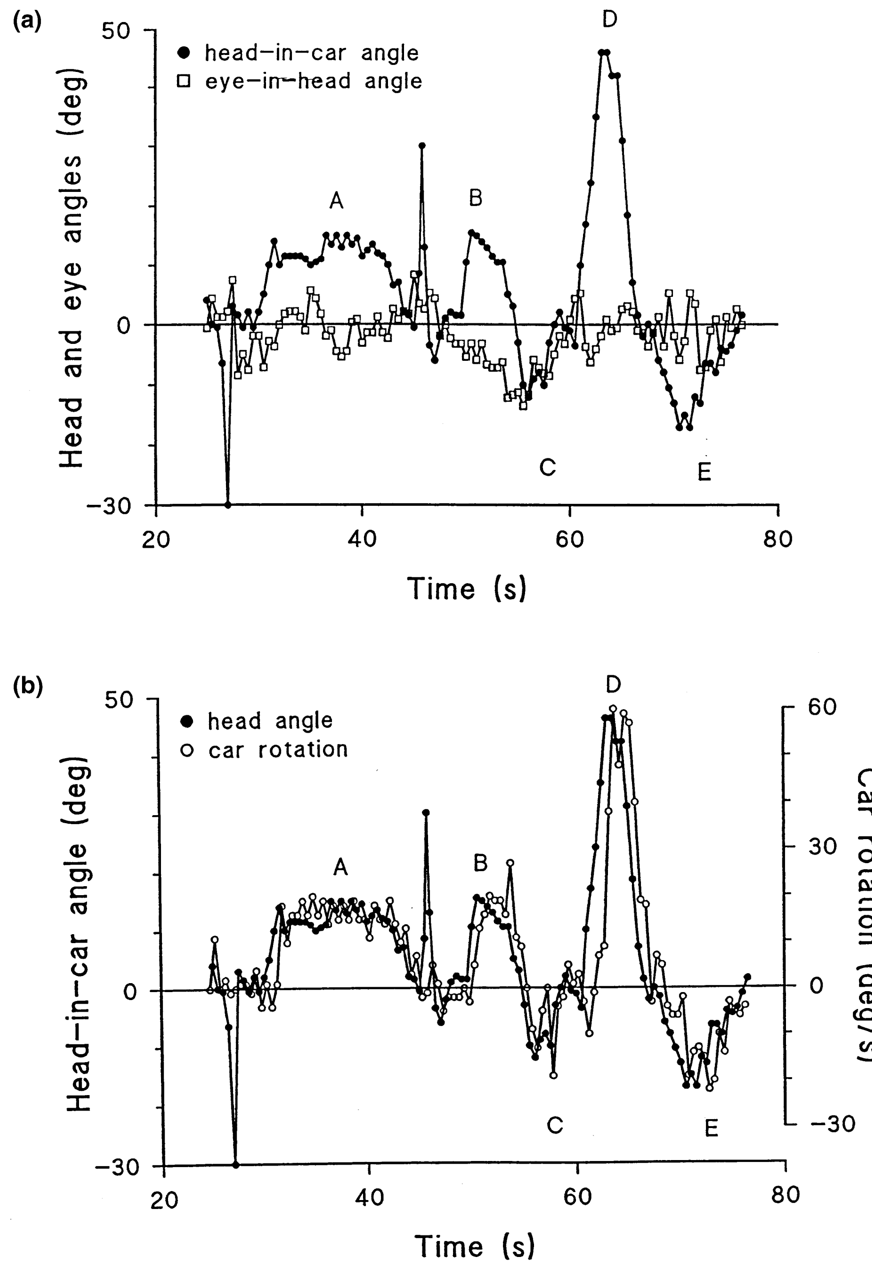
Histograms of gaze direction, measured at 0.2 s intervals, in relation to the tangent points on the five bends. Although the mean direction of gaze (arrow) is near the tangent point on all bends, the distributions are not the same. In bend A, the mean gaze direction coincides with the tangent point, and in bends B, D, and E, it is on the track side of the tangent point; but, in bend C, it is on the grass to the left of the bend. The chart on the bottom right gives the means and standard deviations of gaze direction on each of the first three laps. The differences between the bends (mean 5.0°) are much greater than those between the laps (mean 1.7°). The difference is significant ($p < 0.05$, t test).

of the apex in the field of view through the bend, especially on the short fast bends (B, C, and E) where the racing line clips the apex. This was generally true. On bend E, for example, the position of the tangent point began about 6° to the left of Scheckter's gaze direction; this fell to near zero as the car clipped the apex, then it moved out again to between 10° and 20° as the car exited from the bend toward the straight.

The roles of head and eye

In principle, it is possible to fixate and track a target with the head, keeping the eyes looking straight ahead; or with

Figure 4



(a) Head-in-car and eye-in-head angles as a function of time during the third lap. While head angle is related to bend curvature (in the hairpin [D], the head is turned into the bend through 45°), the eyes are generally directed within 5° of head direction, and their movements are not obviously related to the form of the bends. **(b)** A comparison of the driver's head angle, relative to the car's heading, and the velocity of rotation of the car (lap 3). The two graphs are nearly identical, except for two brief head movements to the left and right at seconds 26 and 44, probably associated with glances off the track, and the fact that the head angle leads car rotation by about 1 s. Laps 1 and 2 were very similar, but a complete record of head movement around the hairpin (D) was only obtainable for lap 3.

the eyes, keeping the head in line with the body; or more commonly using a strategy in which both head and eye mechanisms contribute [3]. As Figure 4a shows, in Scheckter's case, it is the head that performs most of the required movements, while the eyes stay within about 5° of the head axis for most of the time. Overall, 92% of the gaze angle (foveal direction relative to head) is brought about by changes in head direction, and only 8% is brought about by eye movement. Notice that the movements of the head reflect the bends in the circuit: on the right-hand bends (A, B, and D), the head moves to the right, and on the left-hand bends (C and E), it moves to the left. Bend B is peculiar in that the head is directed to the right (the direction of the bend), but the eye moves to the left. This odd behavior was very consistent from lap to lap.

The hairpin (D) was the other part of the circuit in which it appeared that the eye and head had different agendas. Coming up to the bend, there is a series of striped panels on both sides of the road and in front (Figure 2c). Scheckter made repeated saccadic eye movements from the panels to the tangent point on the right and back again in the 3 s preceding the start of the bend (Figure 2c,d). The head itself made a single simple movement from the direction of the road center to the tangent point, 1.5 s before the start of the bend. In the 6 s leading up to the bend, the car's speed came down from 125 mph (56 m/s) to 35 mph (16 m/s), and it seems likely that Scheckter was using the striped walls of the bend as an aid to braking, possibly by monitoring the way the image of the pattern expanded as he approached it. During the hairpin itself, Scheckter turned his head as much as 45° to the right (Figure 4a). This seems not to be unusual: plate 37 in [4] shows photographs of Juan Fangio and Stirling Moss both making head turns of similar size while negotiating a hairpin during the Belgian Grand Prix of 1955.

In an earlier study of a driver's eye and head movements at an intersection [5], both head-in-car and eye-in-head angles correlated strongly with gaze direction (r = 0.99 and 0.93, respectively). Here, the head-in-car correlation is almost as strong (r = 0.96), but the correlation with eye-in-head position is much weaker (r = 0.3), as can be inferred from Figure 4a. Such dissociations between eye and head movements have been reported from laboratory studies [6, 7], but most authors agree that close coupling between head and eye is the normal pattern.

Head direction and steering

The greatest surprise of this study was the finding that the driver's head angle relative to the car's axis was very closely related to the rate of rotation of the car's heading (Figure 1b). The steering wheel angle was not available directly, but the rotational speed of the car (proportional to the product of the steering wheel angle and speed) could be measured from the movement of distant objects such as trees and buildings across the forward-directed part of the field of view of the head-mounted scene camera. The movement of the head itself, which would contribute to this motion, was subtracted from the raw measurement. The result is shown in Figure 4b. (Concern about the accuracy of this somewhat indirect method was partly allayed by cumulating the individual image movements around a complete circuit. This should give a rotation of 360°: in fact, it gave a rotation of 342°, an overall accuracy of 95%). The two curves for head direction relative to the car and rate of rotation of the car are virtually identical, apart from a lag of about a second and the presence of two brief head turns at seconds 27 and 46, which are clearly unrelated to the overall pattern. The maximum correlation (r = 0.94, $p < 0.001$) between the two graphs in Figure 4b occurs after a lag of about 0.9 s (head leads rotation speed). Head direction is a better predictor of rotation speed than gaze direction (r = 0.90), and eye-in-head direction is unrelated to car rotation (r = 0.08).

Why should such a close relationship exist? The conventional explanation would be that the head is directed by vision to the tangent points, and the head's direction, relative to the car's heading, is then used as the input signal for steering and speed control (the "tangent point strategy"; see [1]). There are three problems with this explanation. First, Scheckter's vision is not usually directed *at* tangent points (as in normal driving), but only close to them (Figure 3). Second, there are parts of the track, notably bend E, where the relationship between tangent point direction and rotation speed is weak but the relationship between head direction and rotation speed remains strong (Figure 4b). Third, the peak correlation between head direction and rotation speed occurs approximately 0.3 s earlier than the peak correlation between tangent point direction and rotation speed, making it very unlikely that it is tangent point direction that drives head direction. An alternative explanation, consistent with these three points, inverts the cause and effect relationship: it is the steering intentions of the driver that determine head direction, not the other way round. This argument relies on the fact that Scheckter is very familiar with this circuit and has already developed a racing line around it. Once he has his "rhythm" (his word) after a few laps, all he needs are timing cues and a visual confirmation that the line he intends to take is indeed being adhered to. This is quite different from a normal driver on a road he does not know, where the locations of tangent points are the principal, if not the only, guides to steering.

To develop this argument, we need to specify the way that car rotation and head direction might share the same control signal. Car rotation speed is the product of forward speed and the steering wheel angle. For a racing driver, speed and bend curvature are related because of the need to keep speed just below that which would cause the car to lose its lateral grip. This predicts a square-root relationship between speed (s) and radius of curvature (r) of the racing line itself ($s \propto \sqrt{r}$; see [4], p. 40). The steering wheel angle is directly related to bend curvature ($1/r$), so the car's rotation speed should be proportional to $\sqrt{r} \times 1/r$, or $1/\sqrt{r}$. From this, it follows that the steering wheel angle should be proportional to the square of car rotation speed, and forward speed should be proportional to the reciprocal of car rotation speed. Car rotation speed is thus directly related to both aspects of the driver's "motor program", steering and speed control. And, if the driver has developed a curvature map of the circuit (which he almost certainly has), this can be used both to drive the car and to move the head in the way we observe. For reasons given in [2], p. 168, turning the head by an amount proportional to $1/\sqrt{r}$ (with the appropriate multiplier) will automatically bring its axis into approximate alignment with the tangent points on the bends.

But why move the head at all? We suggest that the answer is probably that the driver still needs to observe the changing locations of the tangent points to check his timing and his racing line. There isn't much else on the track that he could use for this. He will see them changing their positions in his field of view from a standardized viewpoint related to his driving intentions a second later. These movements thus constitute a set of visual expectations that correspond with his intended course. If these expectations are fulfilled, then his line is correct; if not, the discrepancies can be used as error signals to correct or modify his line. He has a second to do this (Figure 4b), which is a reasonably long time; in fact, it is roughly the same as that available to a normal driver responding to changing tangent point locations [1].

It would be of great interest to study the eye movements of a racing driver as he learned a new circuit. We imagine that he would change gradually from a strategy driven by the location of tangent points in his visual field to one driven primarily by memory, as proposed here. The outcomes would not look very different in eye/head direction terms, but presumably, the latter would make for a much smoother (and faster) performance.

Finally, it is interesting that neither Tomas Scheckter nor the ex-Formula 1 driver John Watson, whom we consulted, claimed any knowledge of what they might be doing with their heads and eyes. And Taruffi [4], who gives textbook accounts of the way drivers should deal with different bends, does not once mention where a driver should *look*. As in other visually demanding activities, such as sight-reading music or playing ball sports, the oculomotor system learns to play its part in the activity without instruction or insight.

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